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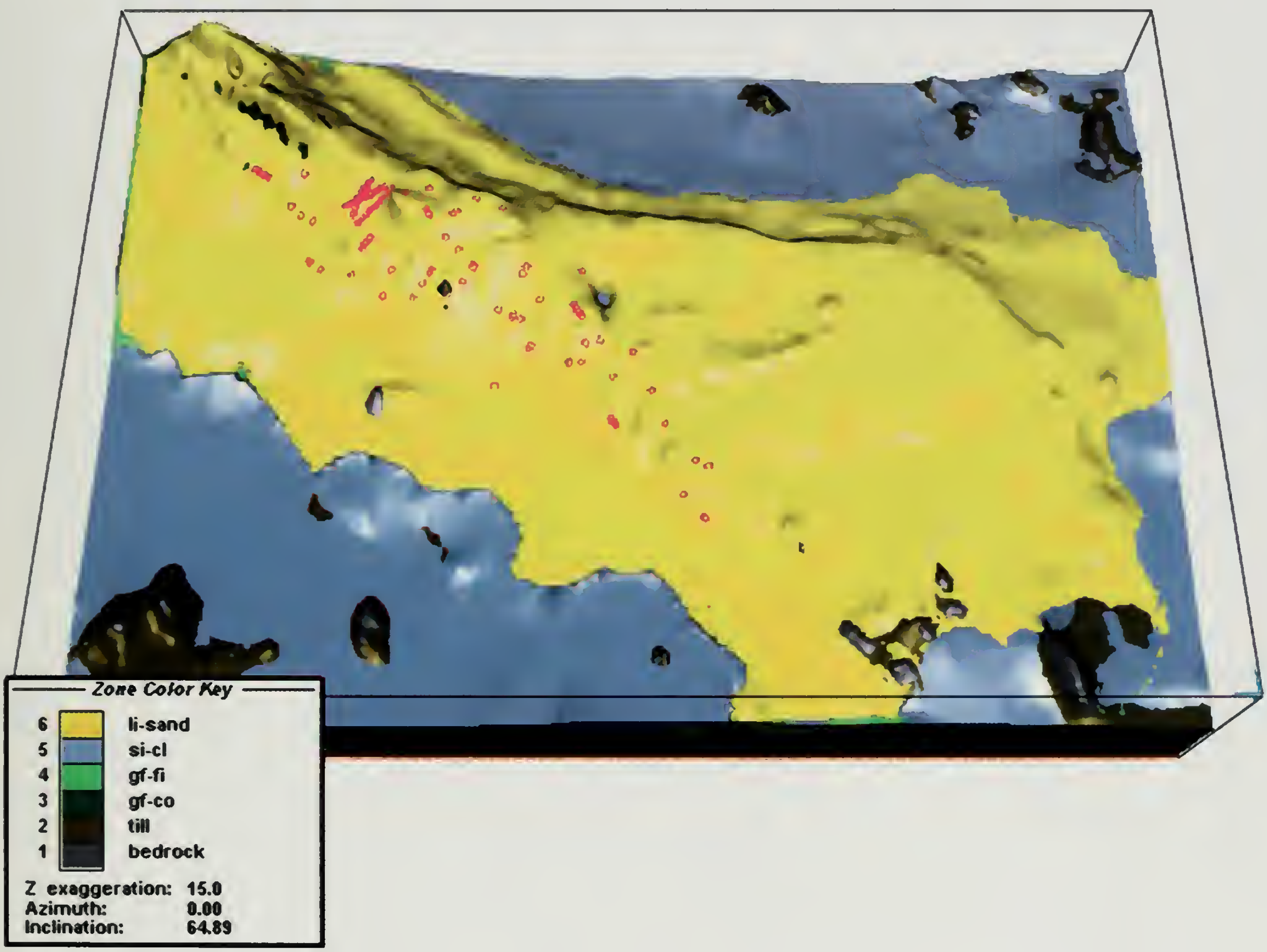

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Cover photo: Locations of the observed kettle holes placed on the 3-D model as an annotation file (red dots).

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ISGS Illinois State Geological Survey

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Constructing a Three-dimensional Geologic Model of the Virttaankangas Aquifer, Southwestern Finland: Methods Applicable to Illinois

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ABSTRACT

As part of continued cooperative work between the Illinois State Geological Survey (ISGS) and Finnish colleagues at the University of Turku, a three-dimensional (3-D) geological model was created to characterize and visualize the Virttaankangas glaciofluvial/glaciolacustrine complex, which is one of the biggest esker systems in southwestern Finland. The 3-D model was developed to provide water resource administrators with a plan for pumping river water to the esker for storage within the esker system, creating an artificial groundwater reserve for the city of Turku and its surrounding area. About 1.3 $m^3 \cdot s^{-1}$ of river water will be infiltrated into the aquifer. Data were prepared at the University of Turku, and EarthVision© geologic modeling software was used at the ISGS to create the 3-D model of the aquifer. The techniques used for constructing the model and visualizing outcomes were specifically designed to provide an easy-to-use tool to guide the choice of infiltration sites for the river water and satisfy the needs of a private utility. These techniques are directly applicable to current geologic mapping efforts being conducted in Illinois.

Since the 1960s, numerous studies of the Virttaankangas aquifer have been performed, including drilling, acquisition of sedimentological logs, and geophysical investigations. The quality and the quantity of the data vary greatly. The data were supplemented by recent sedimentological interpretations of the area and then used to produce a 3-D solids model that represents the geometry, interrelationships, and hydrostratigraphy of the study area. The model represents a simplification of the major hydrogeologic units of the aquifer and provides a new framework to evaluate and modify the conceptual model of the aquifer for eventual development of groundwater flow models.

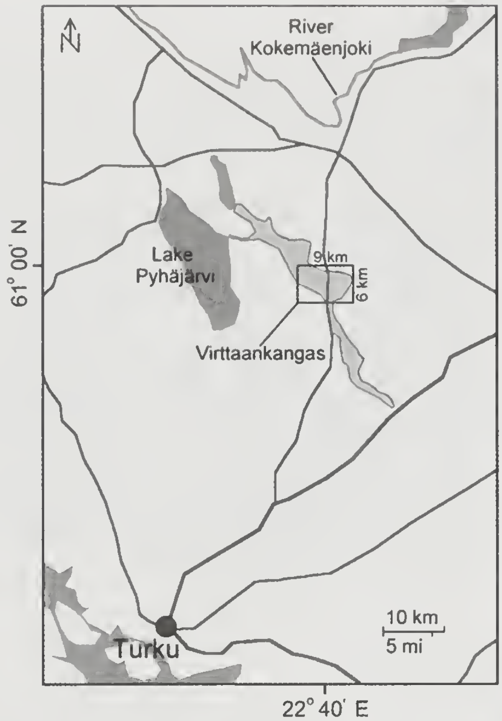
INTRODUCTION

Ongoing cooperative work between geologists at the Illinois State Geological Survey (ISGS) and colleagues at the University of Turku in Finland have produced a three-dimensional (3-D) geologic model of the Virttaankangas glaciofluvial/glaciolacustrine complex, one of the biggest esker systems in southwestern Finland. The 3-D model was developed specifically to provide water resource administrators with optimum management plans to pump river water to the esker for storage, creating an artificial groundwater reserve, and then pumping the water out of the aquifer for the city of Turku and its surrounding area. Because procedures for constructing 3-D geologic models of glacial deposits are largely unpublished, the methodology described in this paper serves as a blueprint for development of 3-D geologic models in Illinois and in other glaciated regions of North America and Europe. Techniques for constructing the model, visualizing complex geology, and working with private industry to provide an easy-to-use tool to guide water management options are directly applicable to mapping currently being conducted in Illinois.

About 60% of Finland's population presently uses groundwater as a source of drinking water, and this percentage has increased substantially in recent years. Contributing to this increased reliance on groundwater are the plans of some of Finland's biggest cities to replace current surface water supplies with natural or artificially infiltrated groundwater. The city of Turku and the surrounding municipalities plan to provide their 285,000 inhabitants with artificially infiltrated groundwater by 2007 (Jaakko Pöyry Infra 2001). The River Kokemäenjoki, the initial source of the infiltrated water, is located 28 km north of Virttaankangas. The plan calls for 1.3 $m^3 \cdot s^{-1}$ of river water to be infiltrated to the Virttaankangas sand and gravel esker aquifer, located 66 km north of Turku (fig. 1). The groundwater is then to be piped from the Virttaankangas aquifer to the Turku area. Following completion in 2007, this project will be one of the largest artificial recharge groundwater projects in northern Europe.

The process of creating an artificial groundwater reserve is by no means trivial. The procedure for introducing the water into the aquifer and the various geologic features affecting its infiltration must be carefully considered. The sprinkling method (fig. 2) under consideration does not require removal of the organic layer of the soil, which would significantly affect the chemical reactions of the water in the infiltration process (Lindroos et al. 2001, Vuorinen 2001). To date, results of artificial recharge tests in the Virttaankangas area have varied (Jaakko Pöyry Infra 2000). Some tests failed because of insufficient information about the 3-D nature of the unconsolidated deposits. In some other tests, infiltrated water was lost outside the capture zones of the water intake wells. The test results showed the need for more precise mapping to characterize the unconsolidated deposits of the Virttaankangas aquifer and resulted in this cooperative mapping project to produce a 3-D geologic model of the area. For more complete discussions of artificial recharge in Finland, see Kivimäki (1992), Lindroos et al. (2001), and Kortelainen and Karhu (2001).

A large amount of data is needed to ensure the accuracy of the 3-D model. Those data include distribution of deposits at land surface, based on interpretations of land forms and soil maps, field examination of exposed materials, and information from shallow excavations or gravel pits. In addition, the subsurface geology should be interpreted based on further field examinations, test hole drilling, sample descriptions,



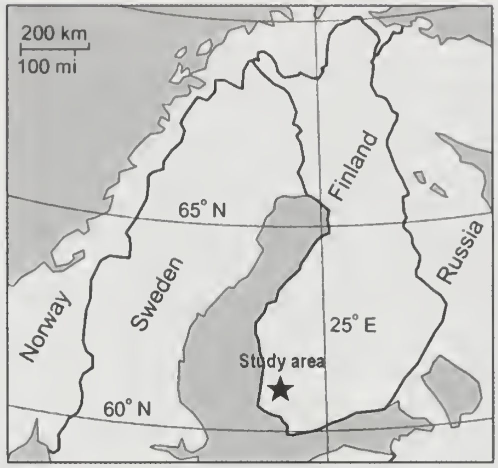


Figure 1 Shaded areas in and outside the Virttaankangas study area (top) represent the largest esker complexes in southwestern Finland.

geophysical investigations, and sedimentological models. Obtaining this additional information often results in large databases consisting of data of variable quality, all of which must be evaluated for possible inclusion into the 3-D model. Sometimes this evaluation procedure includes rejecting misleading or incorrect data (Wilson et al. 1998). Nevertheless, 3-D geologic models are important tools in many groundwater applications (Soller et al. 1999, Berg and Thorleifson 2001, Russell et al. 2001, Walker 2001).

The purpose of this study was to build an internally consistent and fully integrated 3-D geologic solids model representing the geometry, stratigraphy, hydrostratigraphy, and sedimentology of aquifer and aquiclude units for a 54-km^2 area (6 km × 9 km). The model is intended (1) to provide insight regarding the interrelationships of geologic materials and their ability to receive river water and discharge it to a distribution system and (2) to provide answers to the following questions:

- Where should infiltration areas be positioned to avoid the fine-grained units that prevent water flow into underlying coarse-grained aquifer units?
- What are the locations and extents of the coarse-grained aquifer units?
- How should the conceptual model of the subsequent groundwater flow model of the Virttaankangas aquifer be designed to obtain accurate boundary conditions and internal structures for the flow model?

Figure 2 Artificial recharge by the sprinkling method. (Photo courtesy of J. Kääriä, Turku Region Water Ltd.)

To achieve these goals, all of the available previous research data were collected and combined into one database. Data quality was evaluated using the sedimentological model of the study area (Mäkinen 2001, unpublished data; Mäkinen and Räsänen 2003).

DATA

Sedimentological Characteristics

The Virttaankangas esker (officially known as the Säkylänharju-Virttaankangas esker) is an interlobate feature that was formed between the sublobes of the retreating Baltic Sea ice lobe (Punkari 1980, Kujansuu et al. 1995) during the late-Weichselian (Wisconsin Episode) deglaciation of the Scandinavian Ice Sheet. The absence of older glacial deposits suggests that the unconsolidated deposits overlying the Precambrian bedrock were derived from the last glaciation-deglaciation cycle.

The classification of the units included in the 3-D geologic model is based mainly on the depositional model of the Säkylänharju-Virttaankangas complex (fig. 3), which considers the sedimentological studies by Mäkinen (2001, unpublished data) and Mäkinen and Räsänen (2003). Interpretations by Mäkinen (2001, unpublished data) are based on the combined analyses of geomorphologic and geologic data, including morphology of the complex sedimentology of pit exposures, drill hole logs, ground-penetrating radar profiles, seismic soundings, gravimetric and aeromagnetic measurements, and groundwater information, including the results of pumping and recharge tests. Furthermore, the sedimentological processes observed by Mäkinen (2001, unpublished data) from other parts of the esker chain provided an important key to interpret the depositional history in the study area because the same processes apply throughout the esker system (fig. 1) (Mäkinen 2001, unpublished data; Mäkinen and Räsänen 2003).

The geologic and hydrogeologic units that were used for this study were determined collaboratively with J. Mäkinen, the project sedimentologist. During this process, the details of all data were re-evaluated to correlate various data sets and to extract main sedimentary characteristics affecting the heterogeneity of the complex. Detail varied in scale from decimeters to hundreds of meters.

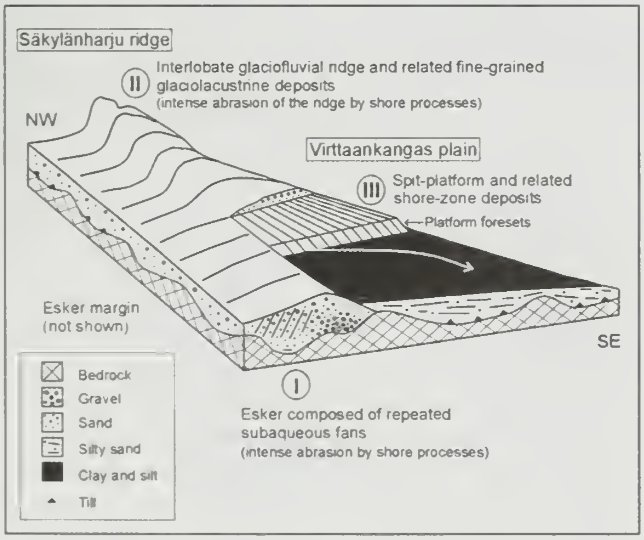


Figure 3 The structural zones of the Säkylänharju-Virttaankangas complex.

Drilling Logs

Thickness of the modeled units was determined mostly from drilling log data from 131 sites (fig. 4). Drill hole data provided information for depths below 20 m and, in many cases, down to 50 m (extending to a maximum depth of 57.6 m). All of the research data were obtained from the archives of the Turku Region Water Ltd., the company responsible for implementing the artificial infiltration project. A digital elevation model (DEM) was used to assign elevations for those data points that lacked elevations. The DEM was also used to assign land surface elevations to published data if the elevations were not presented in the original reports. A fairly complete depiction of the 3-D geologic information of the upper 20 m (including evaluation of the structures, boundaries, and continuity of units) was revealed by studying soil maps (providing information on the uppermost 1 to 2 m of geologic materials), conducting near-surface field investigations, and performing ground-penetrating radar soundings.

Hydrogeologic Units

Groundwater monitoring wells were installed at the 131 sites where drilling log data were obtained (fig. 4). Some groundwater monitoring wells in the eastern and northeastern portions of the coarsest parts of the esker show evidence of a perched saturated zone within and above the uppermost fine-grained unit(s). The aquifer is mostly unconfined, but some portions in the outskirts of the aquifer are confined, based on water level data and observed sediment sequences. Recent isotopic data (see Results and Discussion) support the appropriateness of the hydrogeologic units used in this 3-D modeling study.

Some of the hydrogeologic features of the Virttaankangas complex, including the difference in water levels between the perched water table and the main aquifer unit, had been observed in several earlier aquifer pumping tests (Insinööritoimisto Maa ja Vesi Oy 1972, Maa ja Vesi Oy and Suomen Pohjavesitekniikka Oy 1991, Jaakko Pöyry Infra 2000). The interpretations of the structures and extent of the hydrogeologic units obtained from the aquifer pumping tests were not conclusive, because the interpretations were not based on a sufficiently detailed sedimentological model. In this study, a detailed sedimentological model was used to identify and describe the geologic settings of the area. This sedimentological model was also used as a predictive tool to map the location and extent of the hydrogeologic units presented in the 3-D geologic model.

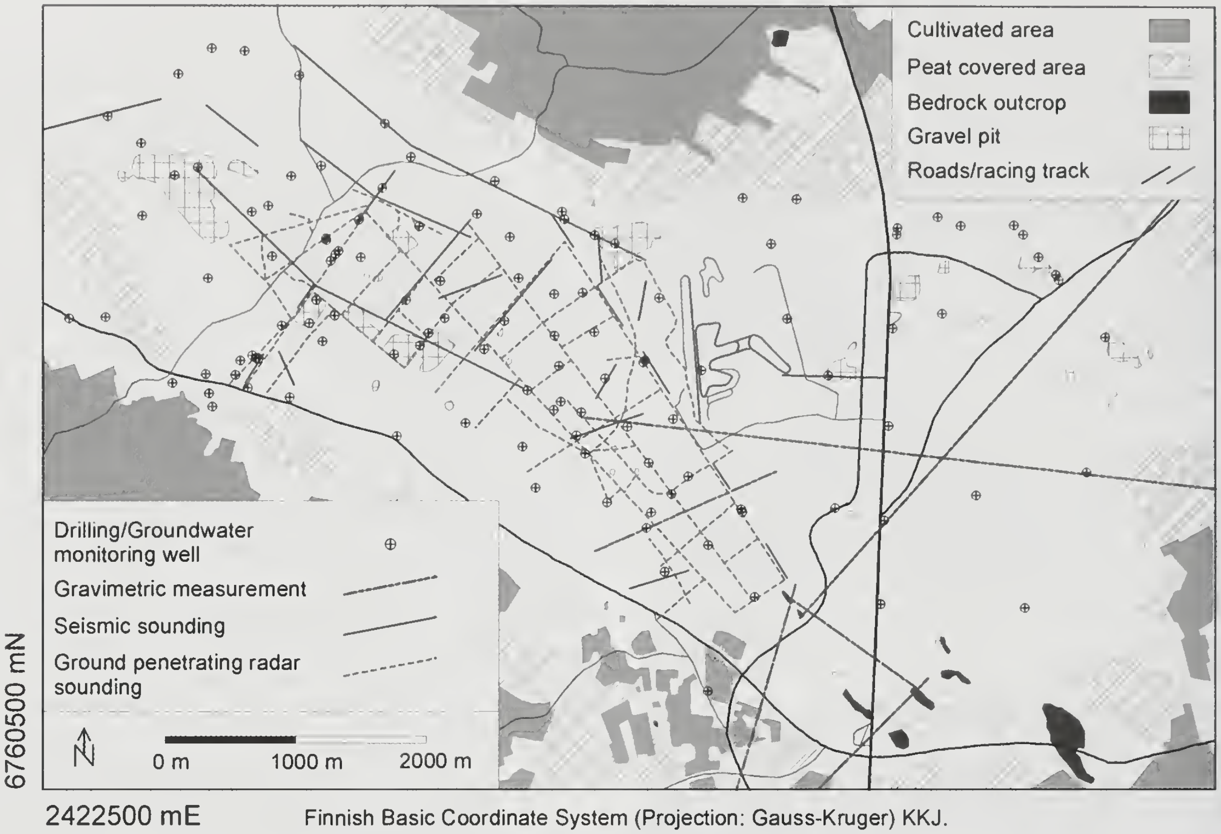


Figure 4 Locations of drillings, monitoring wells, and geophysical studies in the Virttaankangas area.

Gravimetric Measurements

To help evaluate drift thickness, a total of 15.25 km of gravimetric measurements were made in the study area. Thin glaciofluvial materials cover the underlying crystalline Precambrian bedrock, and the densities of these units differ markedly from each other. Gravimetric measurements were calibrated in areas of known bedrock surface elevation (e.g., bedrock outcrop areas). Gravimetric data did not provide information about internal structures within the unconsolidated deposits. Where gravimetric data were absent, seismic soundings and drilling data were used to identify the bedrock surface. Drilling information was used to provide an upper bound for the minimum thickness of glacial deposits in locations where the drilling did not reach the bedrock surface.

MODELING METHODS

The 3-D geologic modeling and data preparation were done with Surfer® and EarthVision© software. The 3-D geologic model of the Virttaankangas aquifer covers a 54-km^2 area and consists of 50-m × 50-m cells in 120 rows and 180 columns. The vertical resolution of the model cells is 2 m.

Sedimentological information, 131 drilling logs, ground-penetrating radar soundings, seismic soundings, gravimetric measurements, permeability tests, and pit observations were used to decide the number of units to be modeled. The following units were identified and modeled:

- relatively impermeable bedrock unit,
- till unit,
- coarse-grained glaciofluvial unit,
- fine-grained glaciofluvial/glaciolacustrine unit,
- glaciolacustrine clay and silt unit, and
- littoral sand unit.

The list represents a simplification of the sedimentary sequences indicated by the data. Thin layers of fine sand, for example, were allowed to appear in the coarse-grained glaciofluvial unit, if these layers were known to be connected with the distal parts of the ice-marginal subaquous fans composing the core of the esker or if the fine sand or silt layers in the coarse-grained unit were caused by deformation structures (e.g., kettle holes). The coarse-grained glaciofluvial unit and the coarsest parts of the fine-grained glaciofluvial/glaciolacustrine unit compose the actual esker. The variable quality of the data required comparison of individual data points with neighboring data of known high

quality (fig. 4). In addition, the information obtained from the high-quality data points had to agree with the sedimentological model of the area. Data incompatibility would have required reassessment of the sedimentological model. The uneven distribution of the available data resulted in varying accuracies of the 3-D model, particularly in areas of low data density (fig. 4).

The number of modeled units was determined based on the quality and quantity of the research data. Cross sections were drawn, and the continuity of the geologic and hydrogeologic units was estimated. Geophysical data were then used to integrate the units observed in the cross sections. At each drilling location, a decision was made concerning (1) the units that were present, (2) unit boundaries, and (3) the degree of correlation with data from neighboring drilling locations. A worksheet containing all of the drilling data was prepared.

A Surfer® database then was created for the surface of each unit. This database was used to create Surfer® matrices; some additional points were used to help constrain the surface in areas where the primary data were absent. These control points either indicated the lateral extent of the units concerned or continued the observed trends in the elevations of the units based on the sedimentological interpretations. The lateral extent of the littoral sand unit, which is the uppermost unit in the esker area, was defined from soil maps, and this information was used to limit the interpolation in EarthVision© software (silt and clay, till, and bedrock are the three uppermost units outside the esker area). For the littoral sand unit, a Surfer® "blanking" file was used to limit the preliminary interpolation within the observed extent of this unit (a Surfer® blanking file automatically replaces the z-values outside the selected polygon with a null value). Outside its limits, the unit's elevation was defined as lower than the next underlying unit in order to obtain the observed limits for the littoral sand unit in the EarthVision© software. Inside its boundaries, the top of the littoral sand unit is at the land surface. Outside the extent of this unit, the silt and clay unit is generally at the land surface.

Data were sparse for the eastern part of the Virttaankangas area, but this region is important because of the presence of the fine-grained material underlying the littoral sand unit and because of the effect of this material on recharge to the lower sand. This silt and clay unit was considered uniform based on the data obtained from the long-term hydraulic head measurements, results of earlier pumping, and artificial recharge tests. The continuity of the silt and clay unit beyond its area of distribution (based on available data) was extended (1) by creating and adding extra data points to support the observed dip of the unit and (2) by limitations on the depositional environment imposed by the conceptual model. Adding extra data points was necessary so that the interpreted trend of the modeled surface extended beyond the modeled study area rather than ending abruptly at the margin of available data.

The presence of the till unit was observed from the drilling logs only. The ground-penetrating radar soundings and seismic soundings did not extend deep enough to image the till unit, and the gravimetric measurements evaluated drift thickness only. On average, the thickness of the basal till in the vicinity of the study area is about 2 m (Kukkonen et al. 1993). The extent and thickness of the glaciofluvial/glaciolacustrine fine-grained unit vary considerably, but the unit's relationship to overlying and underlying units was quite clear at most observed locations.

Some hydrogeologic information was used during the adjustment of the modeled surfaces. The observed extent of the perched water table, for example, is associated with the presence of the glaciolacustrine clay and silt unit. In addition, the location and distribution of the artesian wells in the confined parts of the Virttaankangas aquifer depict the extent of the fine-grained glaciofluvial/glaciolacustrine unit underlying the silt and clay unit.

Integrating the Sedimentological Data into the 3-D Model

The sedimentological model of the study area (Mäkinen 2001, unpublished data) provided information about the geographic limits of the hydrogeologic units and the distribution of geologic materials. The glaciofluvial coarse-grained unit, for example, represents the material deposited by repeated ice-marginal subaqueous fans fed by a subglacial meltwater tunnel (Mäkinen 2001, unpublished data). The maximum areal extent of these subaqueous fans was defined once their proximal parts were located (fig. 5). Mäkinen (2001, unpublished data) identified seven subaqueous fans in the study area. New evidence of one additional subaqueous fan was obtained during the 3-D modeling process after the new interpretation of the bedrock topography that controlled the deposition of these fans was completed. In the areas where the glaciofluvial coarse-grained unit consists of these subaqueous fans, the maximum width of the unit was limited to 500 to 600 m. At the maximum lateral extent of each fan, the thickness of the unit was defined to be 0 m (the upper surface of the unit was defined to coincide with the upper surface of the underlying unit). The glaciofluvial coarse-grained unit adjoins the glaciofluvial/glaciolacustrine fine-grained unit on both sides of the esker.

To increase accuracy in representing the thickness and extent of the units in the model area, extra points were digitized for each unit on the basis of sedimentological information. This procedure provided a more natural interpreted trend of the modeled surface and produced an internally consistent 3-D geologic model where lower surfaces do not

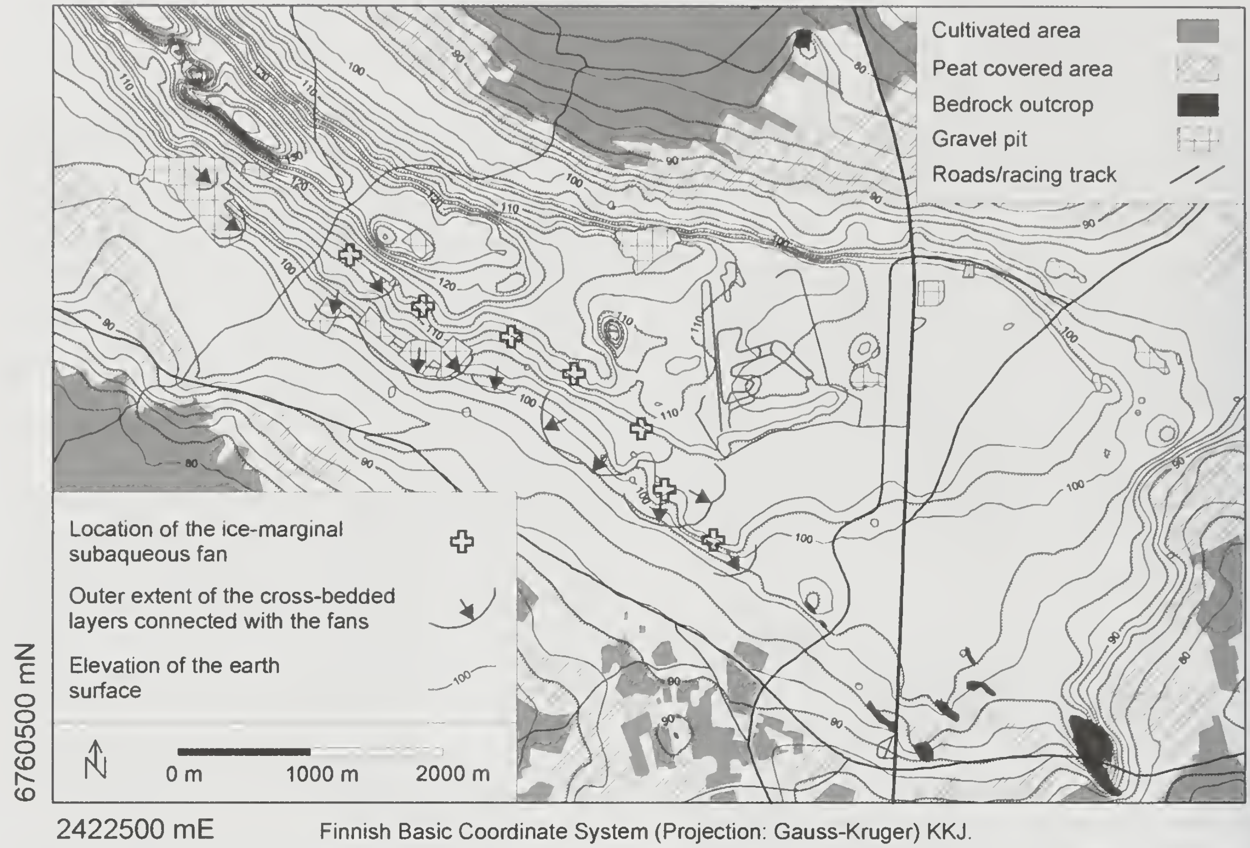


Figure 5 Interpretations of the ice-marginal subaqueous fans. Contour interval is 2 m.

unintentionally project above upper surfaces. Most of the extra points were located in the outskirts of the esker. For example, the bedrock outcrop areas needed to be portrayed in the way they are displayed on the two-dimensional maps of the area. In most of those areas, a thin till cover surrounds the bedrock outcrops. The absence of unconsolidated deposits indicates sediment erosion from areas of higher bedrock elevation from wave action during land uplift. Data from the two-dimensional soil maps were digitized, and extra points, based on geological interpretations, were digitized to integrate these data with the 3-D model data.

Integrating Geology with Hydrogeology

Control over the variation of hydraulic properties within the aquifer is important in groundwater flow models. The advantages of a complex distribution of hydraulic conductivity data in the flow models have been reported by Hill et al. (1998). Therefore, the connection between the geology and hydrogeology had to be clear in the process of making the 3-D model. However, it should be noted that the interpretations obtained from the 3-D model indicate only the relative distribution patterns of hydraulic conductivity, not the absolute values of the aquifer properties. Further work could focus on incorporating more hydrogeologic information into the 3-D model, which was derived mainly from sedimentological and geologic information. The units included into the Virttaankangas 3-D model represent the major hydrogeologic units of the aquifer. An interpretation of the variability of hydraulic conductivity between (and within) the modeled units was presented earlier as a part of this research (Artimo et al. 2003).

Based on the 3-D geologic model, the volume of groundwater in the coarsest parts of the esker (glaciofluvial coarse unit, which includes the ice-marginal subaqueous fans and the ice-marginal crevasse deposits of the Säkylänharju ridge) is about 29,170,000 m^3, and the porosity is estimated to be 25%. Only about 0.39% of this volume will be used by the cities and municipalities of the Turku area on a daily basis.

RESULTS AND DISCUSSION

Validation of the 3-D Model

In some parts of the study area, the Virttaankangas 3-D geologic model was validated by log data from newly drilled wells. Data from previous research efforts did not cover all of the geographic area investigated for the present study, but did provide a hydrogeologic framework. Newly

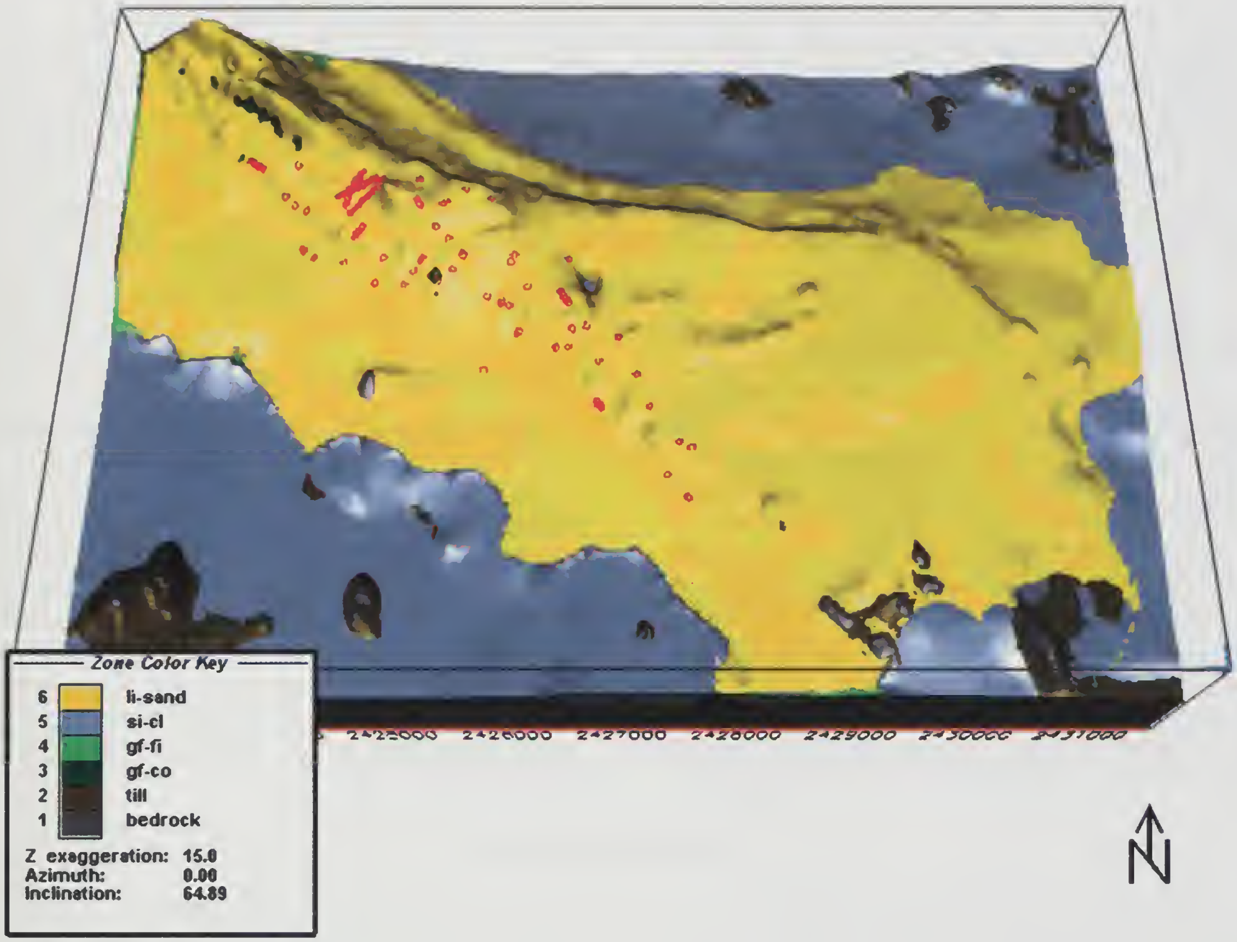


Figure 6 Locations of the observed kettle holes (Mäkinen 2001, unpublished data) placed on the 3-D model as an annotation file (red dots). Observations are mostly based on the ground-penetrating radar and drilling log data. li-sand, littoral sand unit; si-cl, glaciolacustrine silt and clay unit; gf-fi, fine-grained glaciofluvial/glaciolacustrine unit; gf-co, coarse-grained glaciofluvial unit.

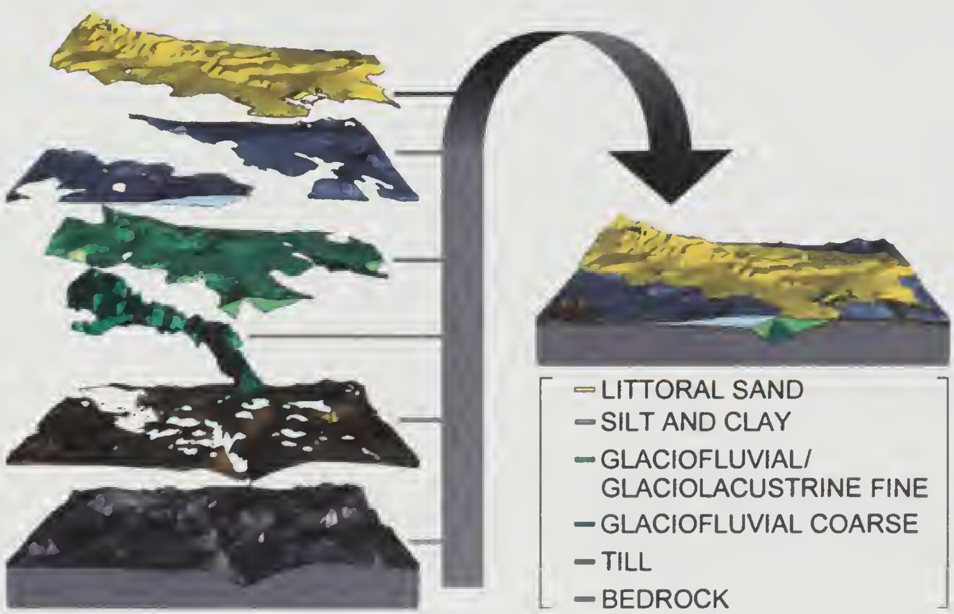


Figure 7 The structure and the hydrogeologic units of the 3-D model.

obtained information correlated well with the 3-D model. The most noticeable deviations between the 3-D geologic model and the new drilling data occurred in individual unit elevations. However, in all of the new drilling locations, the interpreted units were present and are shown in the 3-D model. The largest differences between the modeled data and new drilling data appeared in relation to the bedrock topography, which was expected because of observed variations in the bedrock topography.

Shortcomings of the 3-D Model

The major shortcoming of the 3-D model is the lack of detail within the modeled units. Therefore, precise positioning of the infiltration areas may not be possible without additional site-specific investigations. Recent studies and information obtained from the new drilling logs showed even more complex sedimentary structures in the central parts of the study area than originally thought. For example, the bedrock fracture valley has caused a depression in the surface of the overlying coarse-grained glaciofluvial and fine-grained glaciofluvial/glaciolacustrine units. However, this depression is not topographically visible because it is filled with littoral deposits thicker than 37 m. In other areas of the 3-D model, littoral deposits can extend to 26 m in thickness. In addition, significant internal variation within the modeled units can be caused by kettle holes, which formed when buried ice blocks melted and sediments collapsed into the resulting depressions. These kettle holes (fig. 6) are filled with thin, discontinuous fine-grained layers that may offer preferential pathways for water to infiltrate into the groundwater system. Interpretation of the deformation structures is difficult because the depressions caused by the bedrock fracture valley and the kettle holes occur in the same areas.

Isotopic Analyses

Kortelainen (2001) conducted an isotopic study of groundwater samples obtained in Virttaankangas. The study included measurements of dissolved inorganic carbon, radiocarbon (^{14}C), and tritium. Results strongly support the assumptions that the units described in the 3-D geologic model are the main hydrogeologic units in the Virttaankangas area. Clear differences in the isotopic compositions were found between the perched groundwater, deep groundwater in the coarse-grained esker unit, and deep groundwater in the fine-grained glaciofluvial/glaciolacustrine sediments underneath the silt and clay unit holding the perched groundwater.

CONCLUSIONS

Approaches for creating 3-D geologic models of glacial deposits primarily have been unpublished. This circular provides the blueprint for model construction, including the integration of high-quality point data with a viable sedimentological model, developing innovative ways to visualize complex geology for lay users, and working closely with private industry to answer specific water resource questions, all of which are key to the successful 3-D geologic mapping program in Illinois and directly applicable to constructing internally consistent 3-D geologic solids models of surficial deposits in other glacial environments. A significant amount of preparatory work is needed to select appropriate well log data, integrate those data with geophysical and soil surveys, compare data with sedimentological models, and use various computer software to define layers and build the model. The resulting model is directly usable by hydrogeologists conducting groundwater flow models and by non-geologists working to understand the 3-D nature of a complex glacial environment in order to make wise water management decisions.

The 3-D geologic modeling techniques used for this study portrayed the architecture of glacially derived unconsolidated esker deposits, which typically constitute some of Finland's most significant surficial aquifers. The outcome of this study is an understandable 3-D geologic model usable for water resource planners who want to introduce artificial infiltration of river water into the Virttaankangas aquifer (fig. 7).

The 3-D geologic model is an improvement on existing groundwater flow models. These models include only the deepest aquifer layer and thus lack the ability to represent the effect of the fine-grained silt and clay layer, which can direct the flow of the infiltrated river water outside the main aquifer units into the perched saturated zone. Moreover, the confined flow of the groundwater under the silt and clay layer in the outskirts of the aquifer cannot be represented in the single-layer flow model.

More realistic, more accurate groundwater flow models can be derived using this study's model-building approach and 3-D model. More precise definitions of hydrogeologic unit boundaries are important, especially in Finnish esker aquifers where the properties of geologic materials can vary over short distances. Three-dimensional geologic modeling is needed to build consistent conceptual models for groundwater flow. The experience gained from this study will be used in an ambitious program to model the groundwater flow of the most important aquifers in Finland.

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